Wave-Coherence Measurements Using Synthetic-Aperture Radar

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LONG-TERM GOAL

To develop methods to utilize synthetic-aperture radar (SAR) to characterize wave coherence on scales relevant to the design of mobile off-shore bases (MOB).

OBJECTIVES

There are two basic objectives to this program: (1) to develop the appropriate measures of wave coherence and methods of application for SAR image data, and (2) to apply the methods to available SAR data sets.

APPROACH

Methodology for determining the crest-length distribution using SAR image data, including error metrics, were developed and then validated using available ground truth.

WORK COMPLETED

Methods for characterizing crest-length distributions have been developed and applied to both simulated and actual SAR data. The impact of SAR imaging effects on the results for swell-like conditions has been assessed and guidelines have been developed to mitigate that impact. For more complicated spectra, a variational method for estimating the wave spectrum from the SAR-image spectrum has been developed.

RESULTS

The results of this study are in two parts. First methods for assessing wave-coherence-related quantities directly from SAR-image data for simple swell-like spectra were developed. For more complicated situations, a variational inversion algorithm was developed to determine the wave spectrum from the SAR-image data. The estimated wave spectrum is then used to characterize the wave coherence. The key elements of these two approaches are presented below.

The distribution of wave-crest lengths on the ocean surface can be shown to primarily depend on the directional spread of the wave spectrum. It is well known, however, that SAR imaging effects can alter the apparent directional spread of the wave spectrum. How the SAR imaging effects manifest themselves depends on the wavelength of the waves, the significant wave height, and the SAR look direction relative to the wave propagation direction. To investigate the effects of SAR imaging on the apparent crest-length distribution derived from a SAR image for swell-like conditions (i.e. for a unimodal wave spectrum, relatively Gaussian in shape), a series of forward predictions of the SAR

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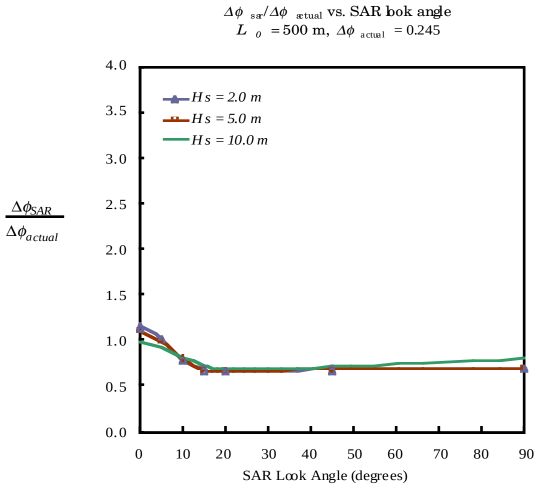

Figure 1: Apparent directional spread $\Delta\phi_{SAR}$ from simulated SAR image normalized with actual directional spread $\Delta\phi_{Actual}$ = 0.105 for various SAR look directions relative to the dominant wave direction for H_s = 2.0 m, 5 m and 10.0 m for λ = 500 m.

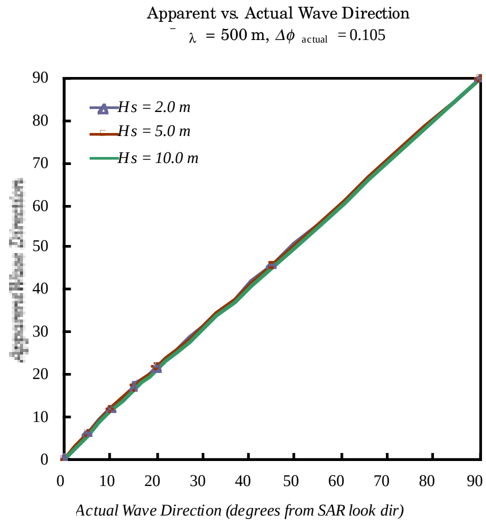

Figure 2: Apparent wave direction for $\Delta\phi_{Actual}$ = 0.105 vs. actual wave direction with H_s = 2.0 m, 5 m and 10.0 m, and λ = 500 m.

image spectrum for known wave spectra were carried out using the Hasselmann formulation [1,2]. Simulations were made over a range of significant wave heights (2–10 m), dominant wave frequencies (0.06–0.09 Hz), and SAR look directions relative to the wave propagation direction. The SAR parameters for the simulations were those typical of satellite SAR sensors (specifically the European Space Agency's ERS platform).

Figure 1 shows the apparent directional spread of the SAR spectrum, divided by the directional spread of the actual wave spectrum, as a function of the SAR look direction relative to the dominant wave direction for three significant wave heights. These results are for a narrow wave spectrum ($\Delta\phi$=0.105 rad) and a dominant wavelength of 500 m. For all wave heights, the error increases with look direction and becomes constant at an apparent directional spread which is about 30–40% too low near a relative look angle of 20°. The apparent narrowing of the wave spectrum is due to the narrow azimuth pass band associated with the SAR imaging process, and the consequent distortion of the wave spectrum. The errors for this case are conservative in the sense that the apparent directional spread would indicate that the crests longer than they actually are. For shorter wavelengths, and larger directional spreading , the effects can be more pronounced.

From figure 1, it is clear that the amount of error in the directional spread determined from the SAR image spectrum depends on the look direction of the SAR relative to the wave direction. The apparent wave direction can be estimated from the location of the peak in the SAR spectrum. Figure 2 shows the apparent wave direction plotted versus SAR look direction for the spectra discussed in figure 1. From the figure, it is clear that the wave direction can be estimated within a few percent from the SAR spectrum under all conditions. Hence, the wave direction can be estimated accurately from the SAR spectrum for swell-like conditions.

For more complicated spectra, ignoring the SAR imaging effects and treating the SAR-image spectrum as if it were the wave spectrum can lead to serious errors. As a result, a variational inversion scheme based on the Hasselmann & Hasselmann model was developed. This effort leveraged and extended

work done on assimilation of SAR data into the SWAN wave-spectrum model under the ONR Advanced Wave Prediction Program. The inversion procedure involves adjusting the wave height spectrum $S(\vec{k})$ so as to minimize the cost function

$$J = \int [\hat{S}_i(\vec{k}) - S_i(\vec{k})]^2 \, d\vec{k}$$

where $\hat{S}_i(\vec{k})$ is the predicted image spectrum and $S_i(\vec{k})$ is the observed image spectrum. The predicted image spectrum is calculated from the equation

$$\hat{S}_i(k_x, k_y) = \iint G(x, y, k_x) e^{-i(k_x x + k_y y)} dx\, dy$$

where $G(x, y, k_x)$ is related to the wave spectrum as described by Hasselmann and Hasselmann [1] and Krogstad [2]. This relationship involves the radar modulation transfer function, for which we use a modification of the expressions given by Plant and Zurk [3]. The change in the cost function due to a small change in the wave spectrum can be written as

$$\delta J = \int P(\vec{k}) \delta S(\vec{k}) d\vec{k}$$

where $P(\vec{k}) \approx [\hat{S}_i(\vec{k}) - S_i(\vec{k})][R_\ell(\vec{k}) + R_\ell(-\vec{k})]$ and $R_\ell(\vec{k})$ is the quasi-linear SAR modulation transfer function. Thus, the cost function can be reduced by changing the wave spectrum by the amount $\delta S(\vec{k}) = -\varepsilon P(\vec{k})$ where $\varepsilon > 0$. Starting with an initial estimate of the spectrum (usually zero), we calculate $\hat{S}_i(\vec{k})$ and $P(\vec{k})$, and change the spectrum using this equation until J is minimized.

Figure 3 shows the change in the cost function as a function of the iteration number for an example ERS data set near Duck, NC. Figure 4 shows the ERS image spectrum, the estimated wave height spectrum after 50 iterations, the image spectrum computed for this wave spectrum, and the wave height spectrum measured at the FRF 8-m array and projected out to the region where the ERS spectrum was measured. Figure 4(a) represents an average of the spectra computed from 16 contiguous 128x128 pixel regions of the ERS image. This average spectrum was corrected for the stationary impulse response function and smoothed using a Gaussian kernel with a width of two wavenumber samples. The directional width of this SAR-image spectrum is about twice that of the FRF spectrum (figure 4d). Applying the same measure to the estimated wave height spectrum results in a width only about 30% larger than the FRF spectrum (as projected to the depth of the ERS measurement). This indicates the utility of the SAR inversion algorithm in improving wave coherence estimates from SAR image data.

IMPACT/APPLICATION

The development of approaches to use satellite-based SAR data to determine wave coherence for MOB design will allow the available archive of SAR data, which spans a number of years, to be used to obtain this information. This may eliminate the need for a costly field-measurement program to obtain this data.

TRANSITIONS

Results were presented at two MOB Technology Exchange Conferences and the 1999 Workshop on Very Large Floating Structures.

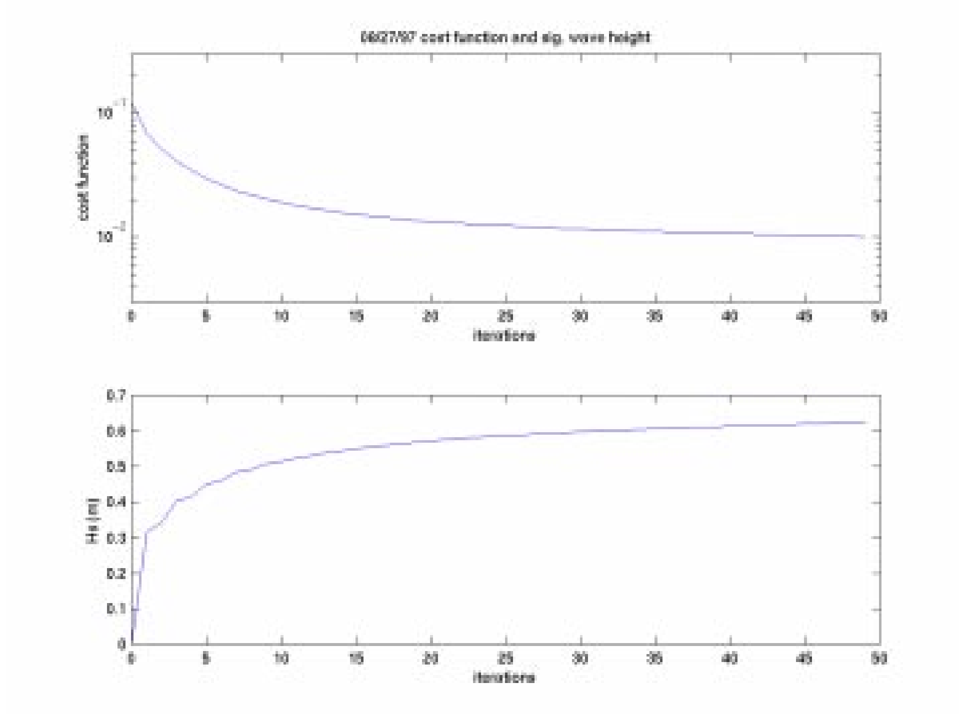

Figure 3. Cost function and significant wave height for wave spectrum estimated from ERS 08/27/97 data set, plotted versus number of iterations.

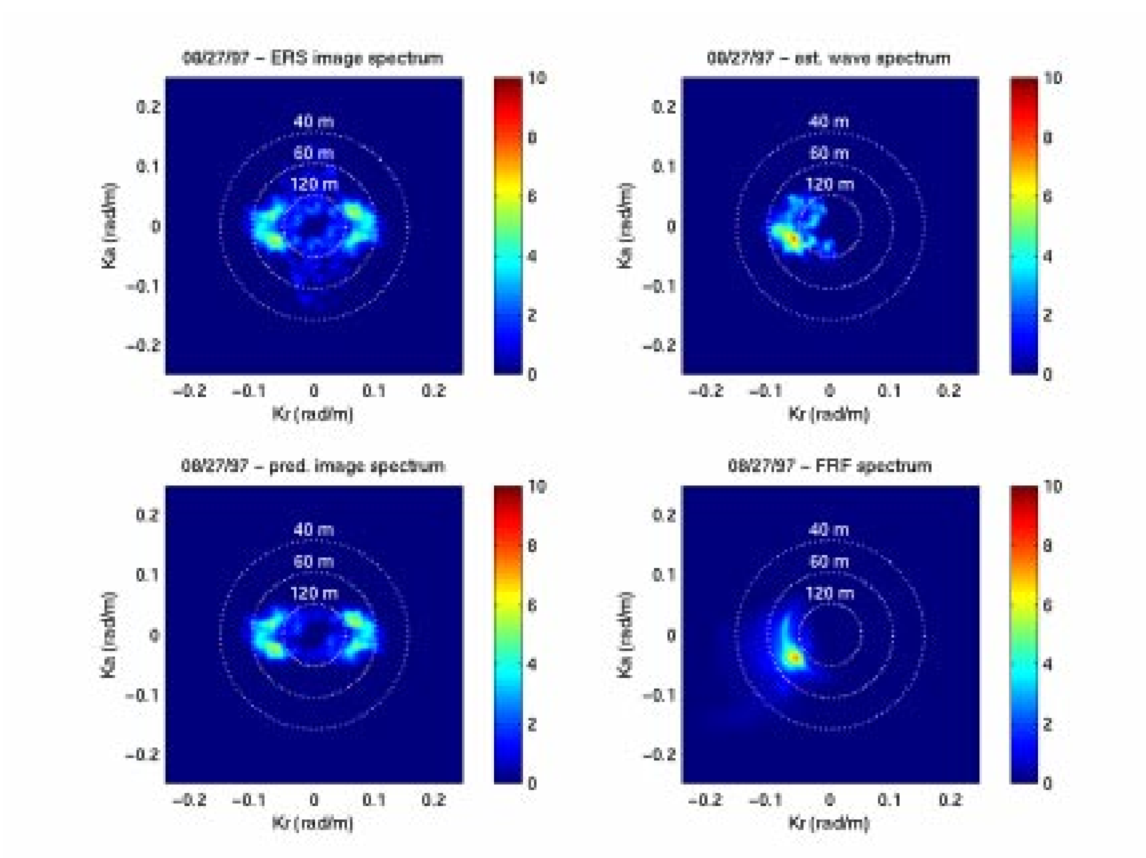

Figure 4. SAR spectrum inversion results for ERS SAR data set collected on 08/27/97 near Duck, NC. (a) ERS image spectrum, (b) estimated wave height spectrum, (c) image spectrum predicted from estimated wave height spectrum, (d) wave height spectrum measured at FRF 8-m array and projected to approximately 20m depth where ERS image spectrum was extracted.

RELATED PROJECTS

This project is related to other efforts under the MOB Wave Coherence program. These other efforts focus on developing both improved measures and understanding of nonlinearity and wave coherence. The basis for the variational approach for estimation of wave spectra from SAR-image data was initially developed under the ONR Advanced Wave Prediction Program (Contract No. N00014-98-C-0012).

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